Late stages of stellar evolution resolved by infrared and millimetre interferometry

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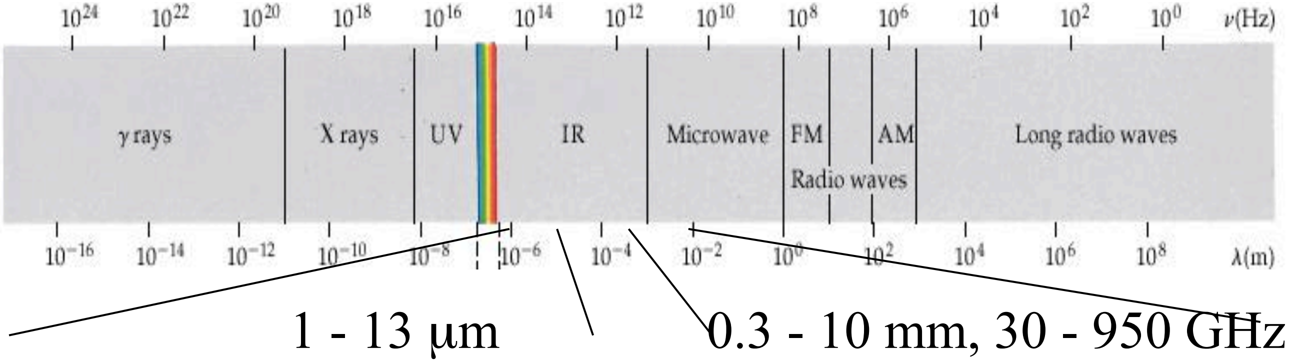
VLTI and ALMA synergy

- ESO provides astronomers with access to two of the largest interferometric facilities of the world



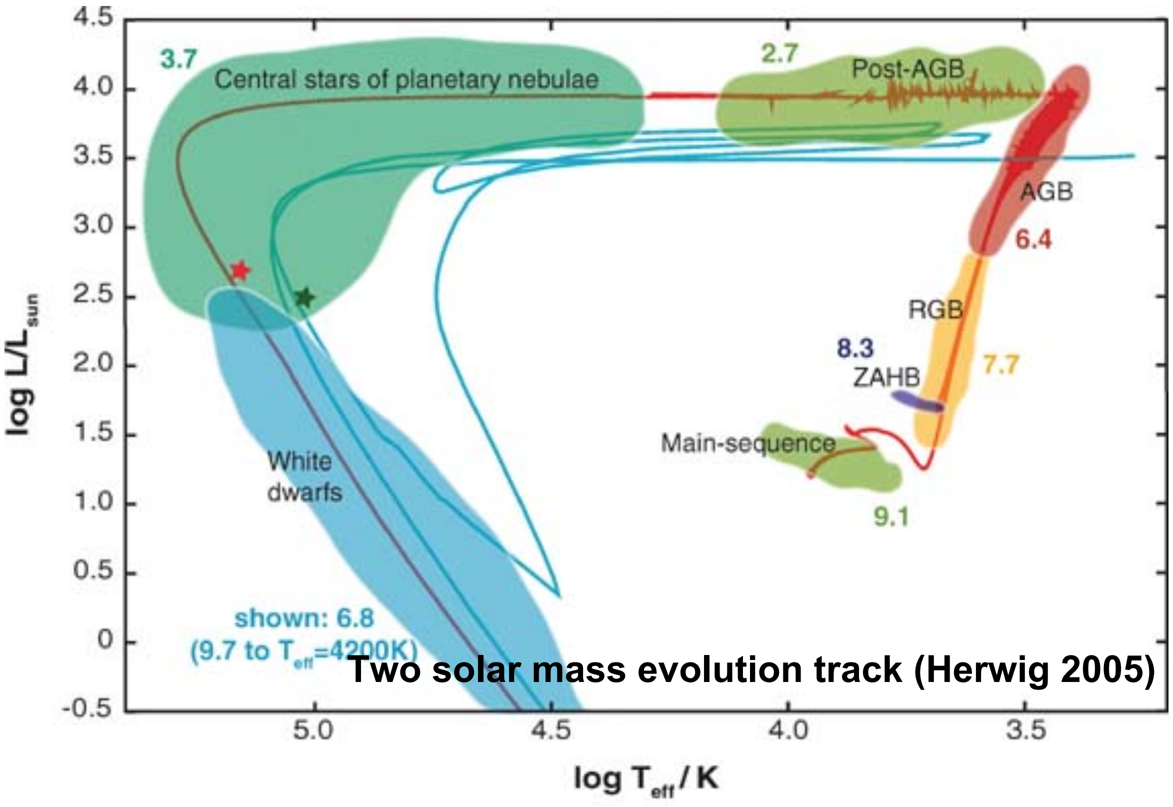
1 - 13 μm

0.3 - 10 mm, 30 - 950 GHz

- Allowing us, for instance, to resolve stellar surfaces and circumstellar environments of evolved stars at infrared and millimetre wavelengths.

Asymptotic Giant Branch stars

- AGB stars represent the last stage of the evolution of low- to intermediate mass stars that is driven by nuclear fusion.
- The most important driver for the further evolution is mass-loss, but which is purely understood, in particular for oxygen-rich stars



Two solar mass evolution track (Herwig 2005)

Structure of an AGB star

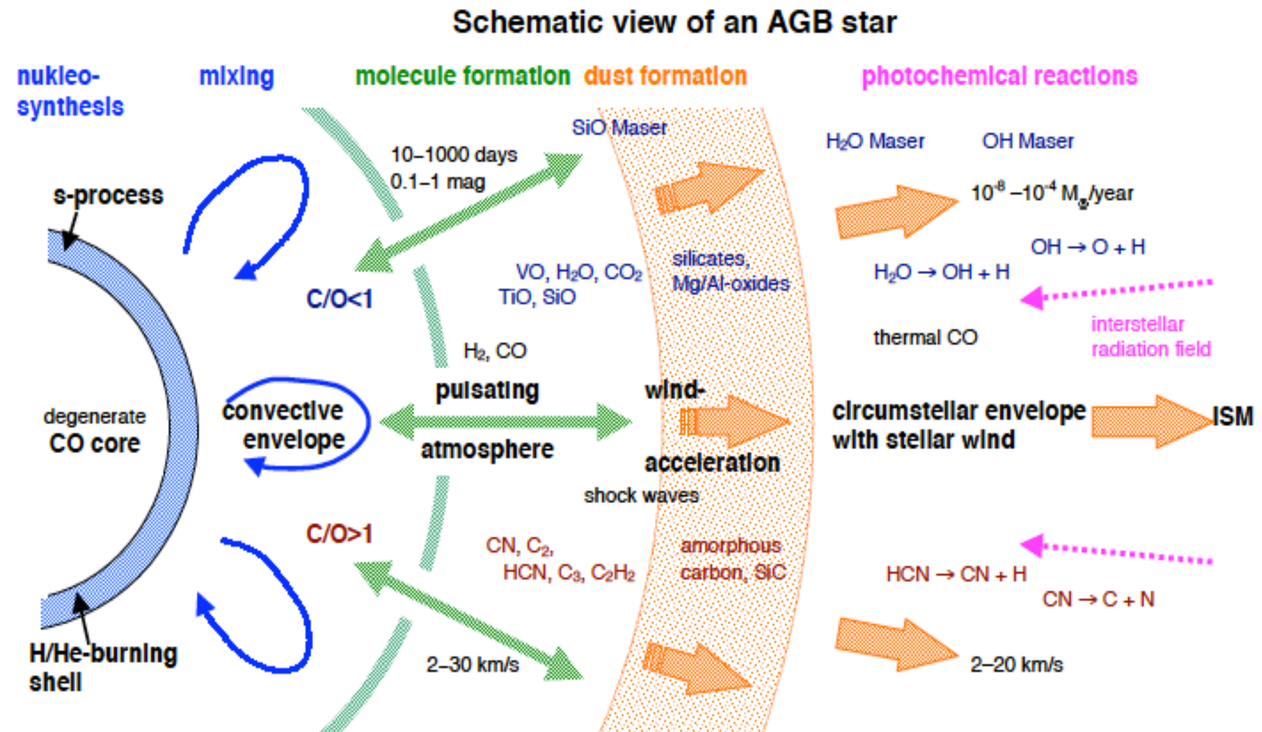


Fig. from J. Hron (after Le Bertre)

VLTI

Stellar photosphere

Molecular layers

Dust shell

ALMA

Radio photosphere

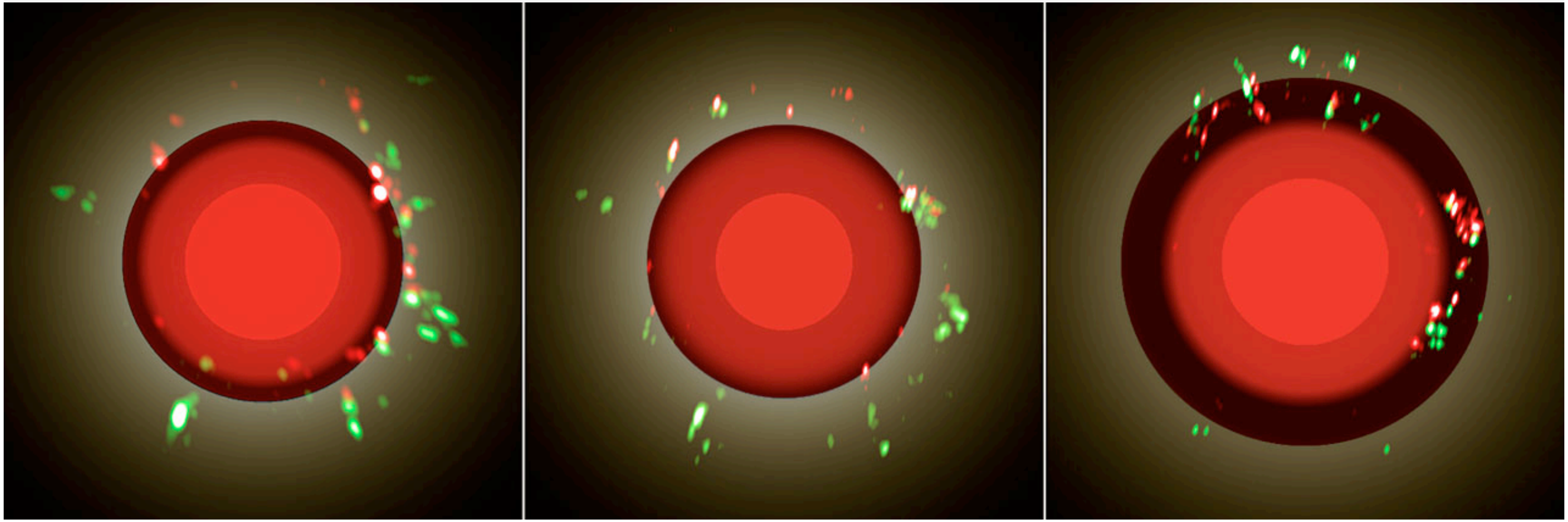
Thermal lines (e.g. SiO, CO, ...)
Abundances, depletion of Si into SiO

SiO maser, high-freq. water maser

AGB stars: Current questions

- How do AGB stars loose mass, in particular in the case of oxygen-rich stars ?
- How is the mass-loss process connected to variability at different scales from pulsation (~1 year) to thermal pulses (10000 years) ?
- When and where do inhomogeneities/clumps/asymmetries form ? Which are the shaping mechanisms ?
- Influence of binary AGB stars on strongly asymmetric shapes in Pne ?

MIDI and VLBA/SiO maser observations of S Ori

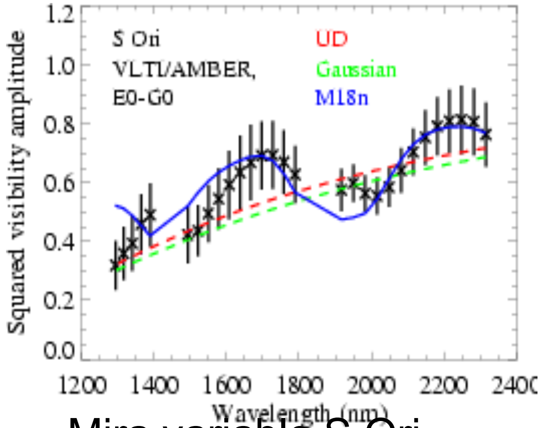


- (red) v=2, J=1-0, 42.8 GHz (green) v=1, J=1-0, 43.1 GHz maser images on MIDI model with photosphere, molecular layer, Al_2O_3 dust.
- Al_2O_3 dust has an inner radius of ~2 stellar radii, and may be co-located with the SiO maser region.
- The location of the SiO maser emission is consistent with earlier such observations and with theoretical models by Gray et al. 2009.
- The maser velocity structure indicates a radial gas expansion with velocity ~10 km/sec.

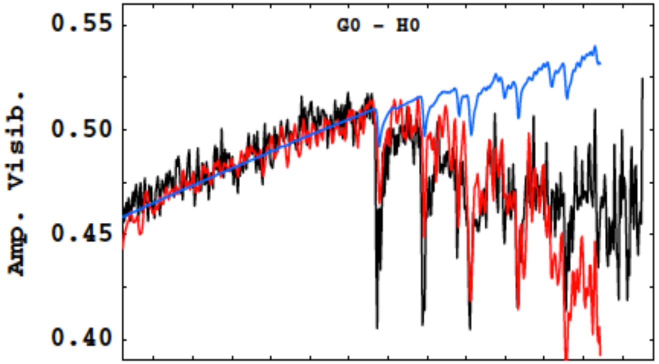
Wittkowski, et al. 2007

AMBER spectro-interferometry of red giants and supergiants

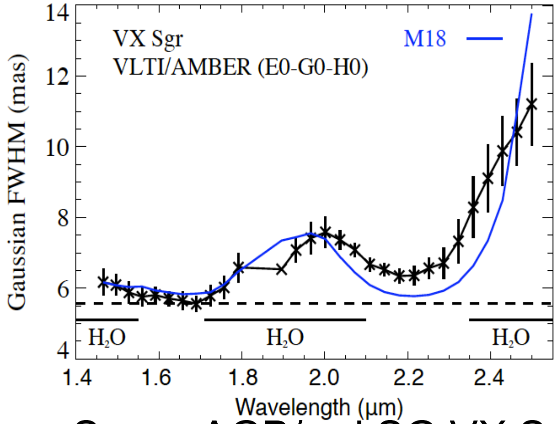
Atmospheric molecular layers of H_2O and CO are a common phenomenon of evolved oxygen-rich stars of different luminosities and mass-loss rates



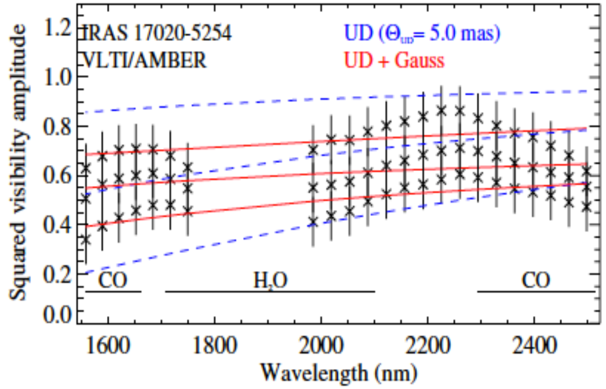
Mira variable S Ori
Wittkowski et al. 2008



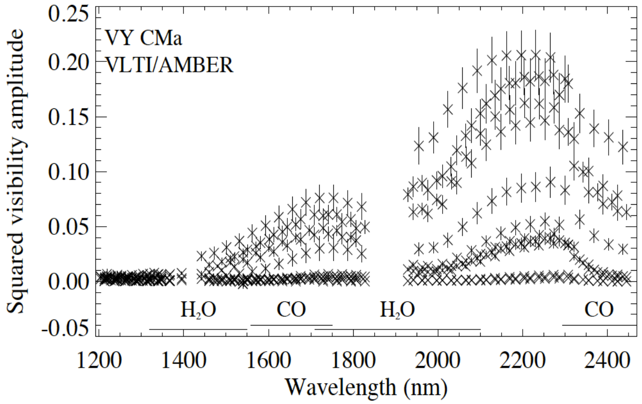
SR variable RS Cap
Marti-Vidal et al. 2010



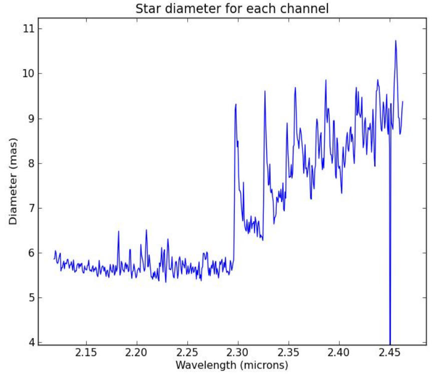
Super-AGB/red SG VX Sgr
Chiavassa et a. 2010



OH/IR star IRAS 17020-5254
Ruiz-Velasco et al. 2011

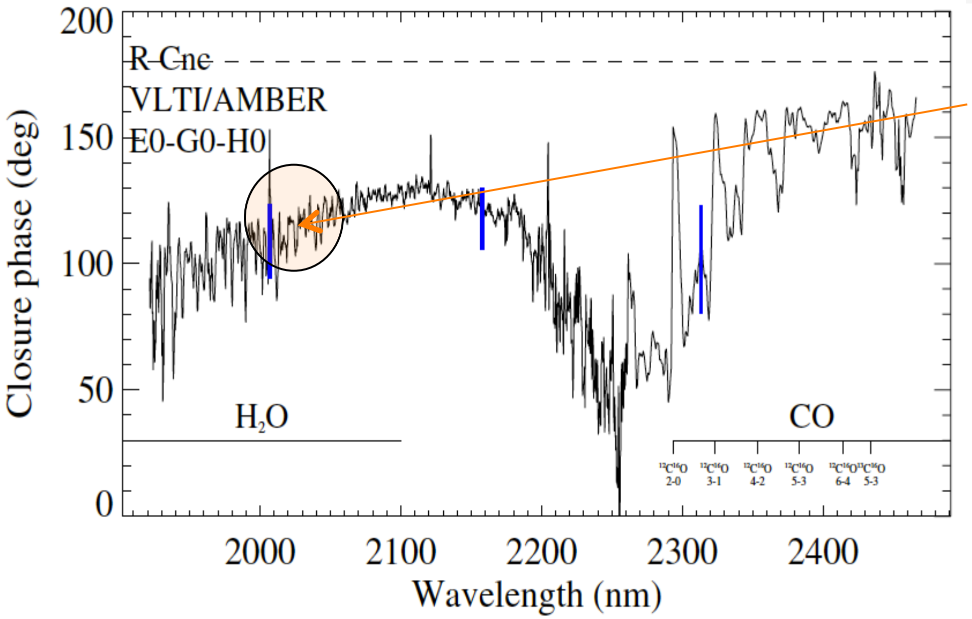


Red SG VY CMa
Wittkowski et al. 2012



Red SG AH Sco
Arroyo-Torres et al., in prep.

Asymmetries at different layers

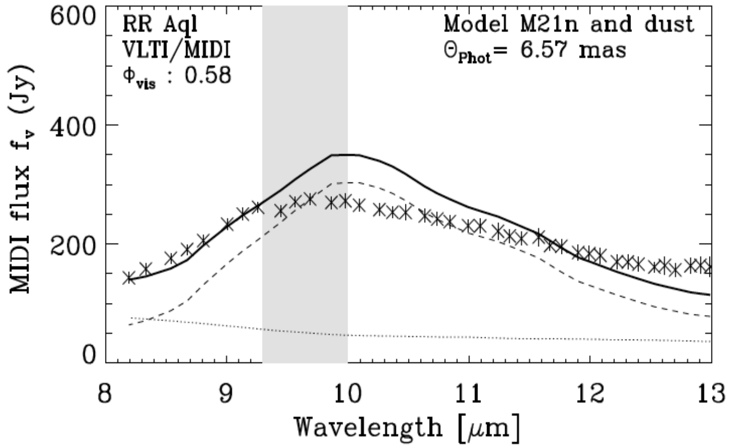


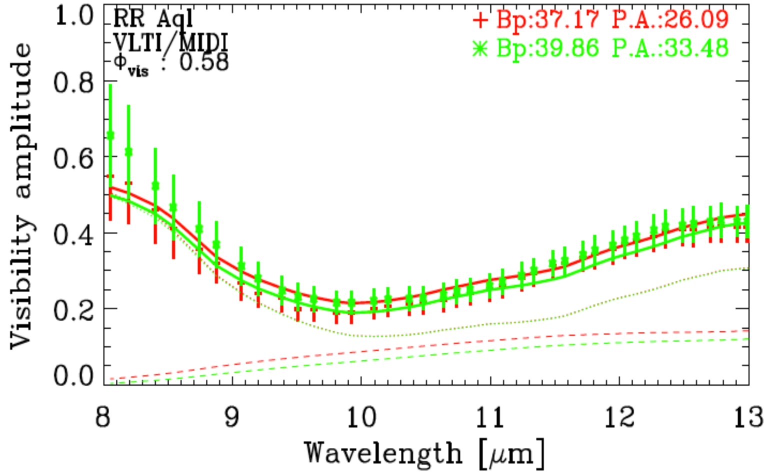
For example, one unresolved spot at separation
4 mas contributing 3% of the total flux

- Wavelength-dependent closure phases indicate deviations from point symmetry at all wavelengths and thus a complex non-spherical stratification of the atmosphere.
- Can be interpreted as a signature of large-scale inhomogeneities/clumps of molecular layers at different radii.
- These might be caused by pulsation- and shock-induced chaotic motion in the extended atmosphere as theoretically predicted by Icke et al. (1992) and Ireland et al. (2008, 2011).

Wittkowski et al. 2011

MIDI dust shell modeling





Model	τ_V (Al_2O_3)	τ_V (silicate)	R_{in}/R_{Phot} (silicate)	p (silicate)	Θ_{Phot} [mas]
M21n	0.0	2.8 ± 0.8	4.1 ± 0.7	2.6 ± 0.3	7.6 ± 0.6

- Modeling approach of a silicate dust shell is well consistent with our data.
- No detection of intra-cycle and cycle-to-cycle variability of the dust shell within our uncertainties; consistent with our modeling approach of adding a radiative tranfer model of the dust shell to dynamic model atmospheres.
- MIDI data not sensitive to an additional Al2O3 dust shell with relatively low optical depth.

Karovicova et al. 2011

Dust condensation sequence

- Additional targets processed in the same way:
- Al_2O_3 dust confirmed with an inner radius of ~ 2 photospheric radii; silicate dust with an inner radius of ~4 photospheric radii.

		Mass-loss rate (lit.)	τ_V	R_{in}
R Cnc	Al_2O_3 dust	0.2 10^{-7} M_{sun}/yr	1.4	2.2
S Ori	Al_2O_3 dust	2.2	1.5	1.9
GX Mon	Al_2O_3 + Silicate dust	5.4	1.9 / 3.2	2.1 / 4.6
RR Aql	Silicate dust	9.1	4.1	4.1

- Dust content of stars with low mass-loss rates dominated by Al_2O_3, while dust content of stars with higher mass-loss rates predominantly exhibit significant amount of silicates, as suggested by Little-Marenin & Little (1990), Blommert et al. (2006).

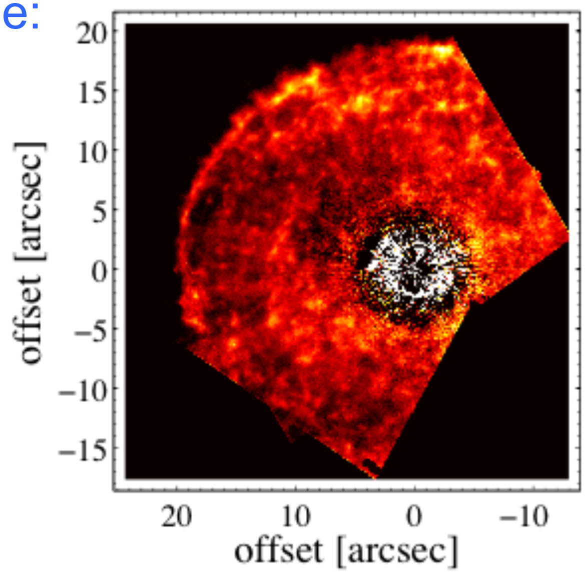
Karovicova 2011 (PhD thesis)

The carbon-rich star R Scl

- Carbon-rich semi-regular variable AGB star
- Period 374 days
- Warm dust shell of amorphous carbon and silicon carbide (SiC)

A detached shell of dust and gas caused by a thermal pulse:

- radius ≈19” (EFOSC2, HST)
- shell v_{exp}≈15 km/s (various single-dish)
- M_{shell}≈2.5x10^{-3} $M_\odot$ (radiative transfer modelling)
- M_{dust}≈3x10^{-6} $M_\odot$ (HST)
- mass-loss rate≈3x10^{-7} $M_\odot yr^{-1}$ (RT modelling)
- present-day v_{exp}=10.5 km/s (HCN observations)



✓ age < 1700 yr
✓ t_{pulse}=200-400 yr
✓ clumpiness indicates wind interaction

BUT

✓ no strong constraints
✓ no model-obs interaction
✓ detailed info only from dust

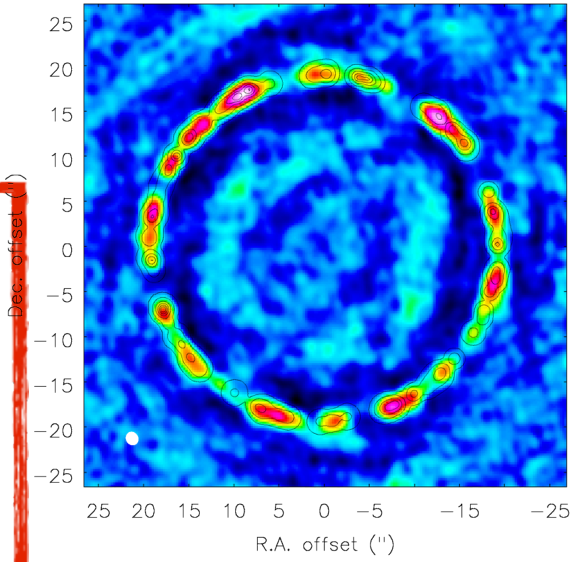
R Scl observed in ALMA cycle 0

Observe the detached shell using the compact configuration of Cycle 0

- bands 3, 6, and 7, mainly target CO(1-0), CO(2-1), and CO(3-2)
- 7, 23, and 45 pointed mosaics, 50”x50” fields
- spatial resolution of 4.3” to 1.4”

Observe the detached shell of gas in unprecedented detail

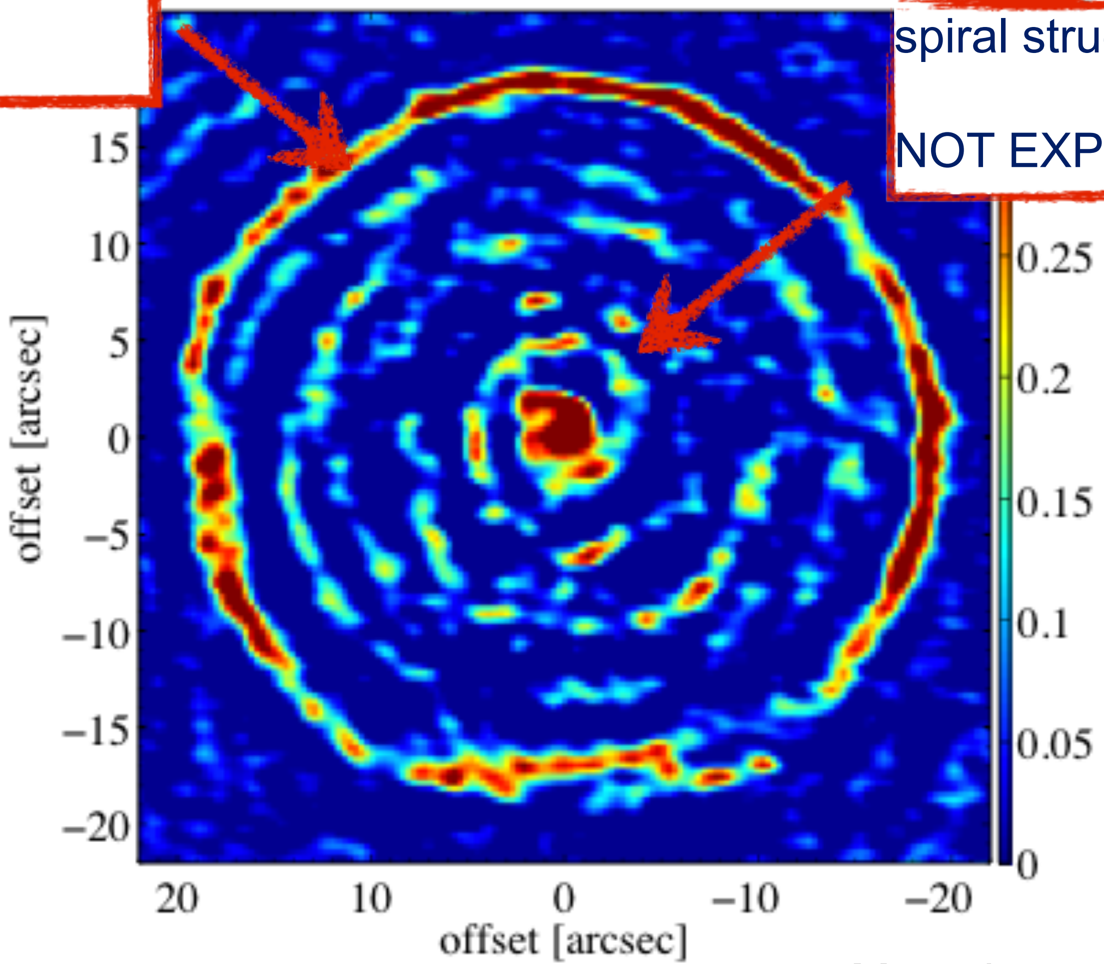
- gas mass, and temperature structure
- gas distribution and clumpiness (angular resolution)
- velocity structure (spectral resolution)
- information on scales comparable to dust observations



CO(3-2) with *simdata*

Team: Matthias Maercker, Wouter Vlemmings, Shazrene Mohammed, Sofia Ramstedt, Itziar de Gregorio, Martin Groenewegen, Elizabeth Humphreys, Franz Kerschbaum, Michael Lindqvist, Lars-Ake Nyman, Hans Olofsson, Claudia Paladini, Markus Wittkowski

ALMA Cycle 0 band 7 CO(3-2)



detached shell

EXPECTED

spiral structure

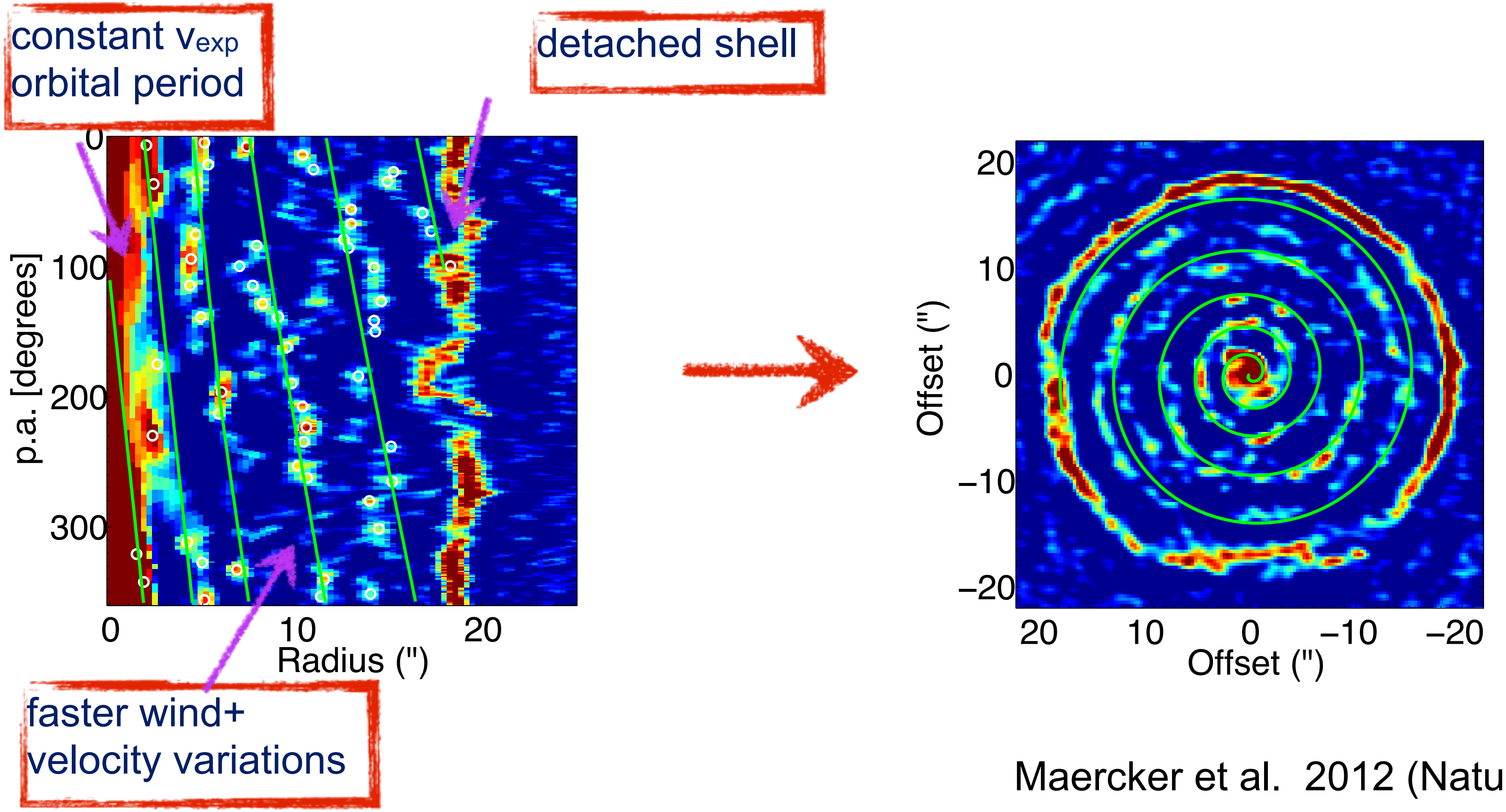
NOT EXPECTED

Maercker et al. 2012 (Nature)

What do we believe has happened?

1) Detached shell due to thermal pulse

2) Spiral structure due to binary interaction



constant v_{exp}
orbital period

detached shell

faster wind+
velocity variations

Maercker et al. 2012 (Nature)

R Scl results

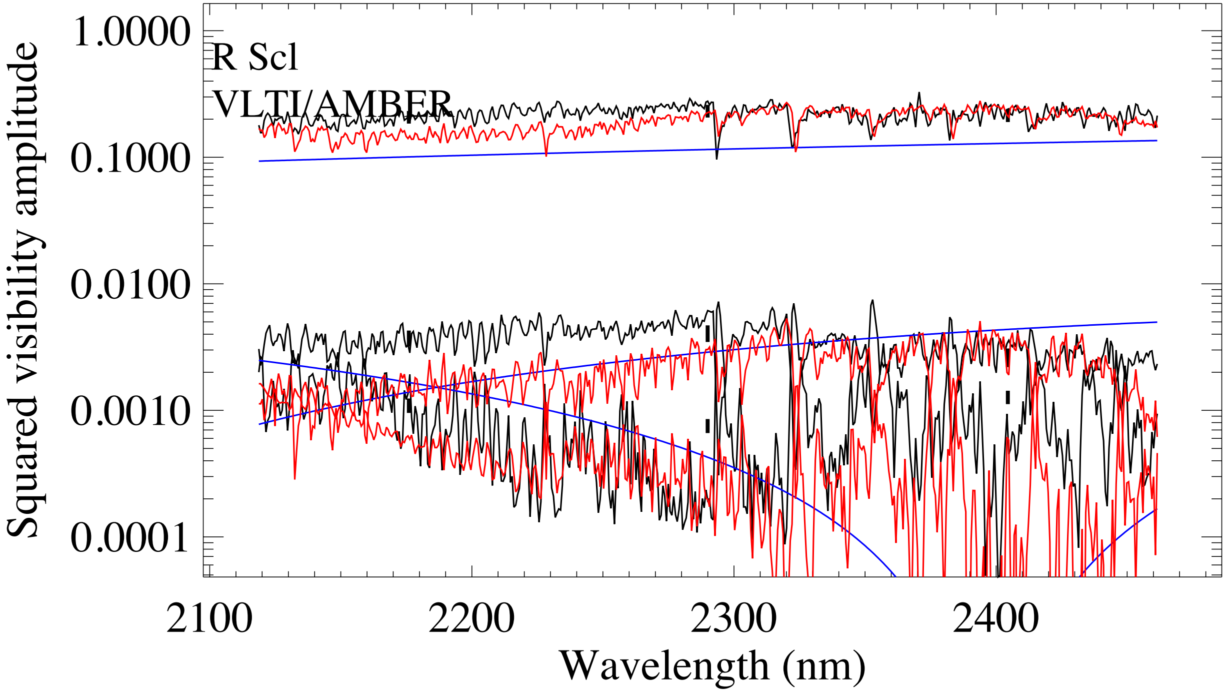
Many results can be obtained directly from the image and knowledge on the present-day mass-loss rate:
orbital period ~ 345 years, shell age ~1800 years, pulse duration < 345 years

Smoothed particle hydrodynamics model:

- $M_{primary}$= 1.6 $M_\odot$, $M_{companion}$= 0.2 $M_\odot$
- orbital period = 345 years, t_{pulse}= 200 years
- pulse mass-loss rate = $2\times10^{-6} M_\odot\,yr^{-1}$, pre- and post-pulse = $2\times10^{-7} M_\odot\,yr^{-1}$

Maercker et al. 2012 (Nature)

AMBER observations of R Scl



Blue line: UD model

Red line:
Dynamic atmosphere model
(Mattsson, Wahlin, Höfner 2010)

- Constraints of the dynamic atmosphere and wind models
- Constraints of fundamental parameters

➢ Feedback to modeling of the ALMA spiral

Wittkowski et al., in prep.

Summary: R Scl observations

- Likely discovery of a previously **unknown** binary companion with ALMA
- The observed spiral allows to verify model results observationally **for the first time!**
- **Observational** constraints on pre-pulse, thermal pulse, and post-thermal pulse evolution
- AMBER constrains inner wind models and fundamental stellar parameters

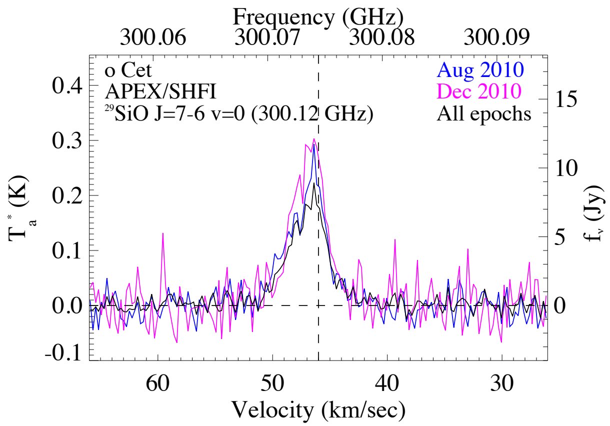
    - refined models of thermal-pulses and nucleosynthesis (ALMA)
    - refined models of dust formation and wind acceleration (VLTI)
    - binary evolution and shaping processes

- Next steps: (1) AMBER imaging scheduled for Oct 2012
  (2) ALMA observations of the inner spiral proposed
  (3) Binary interaction of more sources with different parameters

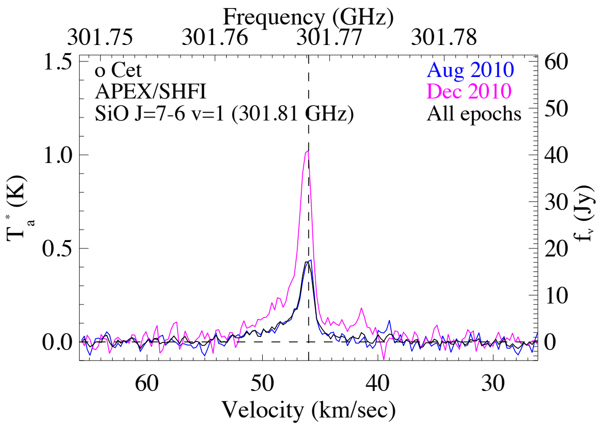
Summary – oxygen-rich stars

- Near-infrared interferometry:
  - complex atmosphere including molecular layers (H_2O, CO, SiO)
  - well consistent with predictions by latest dynamic model atmospheres.
  - complex non-spherical stratification of the atmosphere, indicating asymmetric/ clumpy molecular layers.
  - Shaping may include chaotic motion in the extended atmosphere, triggered by the pulsation in the stellar interior.
- Mid-infrared interferometry:
  - constrains dust shell parameters including Al_2O_3 dust with $R_{in} \sim 2\ R_{Phot}$ and/or silicate dust with $R_{in} \sim 4\ R_{Phot}$.
- SiO masers:
  - lie in the extended atmosphere
  - provide velocity information
  - may be co-located with Al_2O_3 dust and optically thick molecular layers
  - likely connected to the location of a shock front.
- Next steps:
  - AMBER imaging campaign (RR Aql in P89); AMBER monitoring
  - ALMA observations of the SiO emitting regions proposed

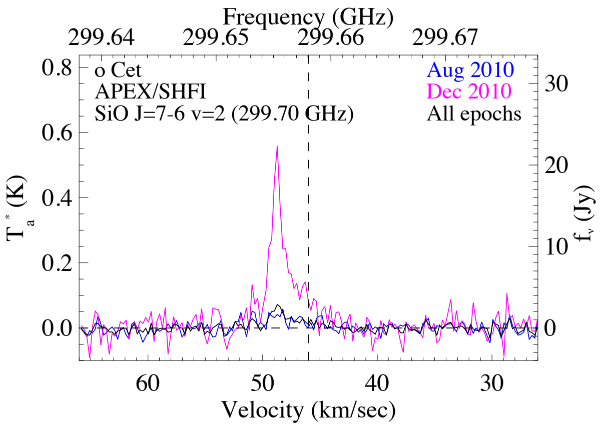
SiO emission toward omi Ceti



v=0, ^{29}SiO



v=1, SiO



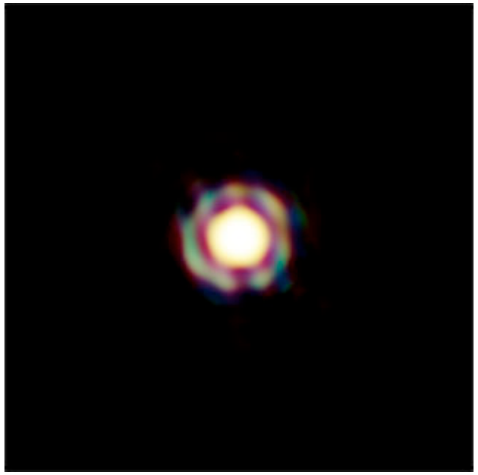
v=2, SiO

- Broad (~10 km/sec)
- Gaussian-shaped
- Centered on systemic velocity
- Small variability with phase
  - Mostly thermal emission
  - Wind acceleration region
  - Extent ~1.2” (PdBI)
- Mass-loss rates
- Depletion of silicon into silicates
- Shaping, clumpiness, elongation

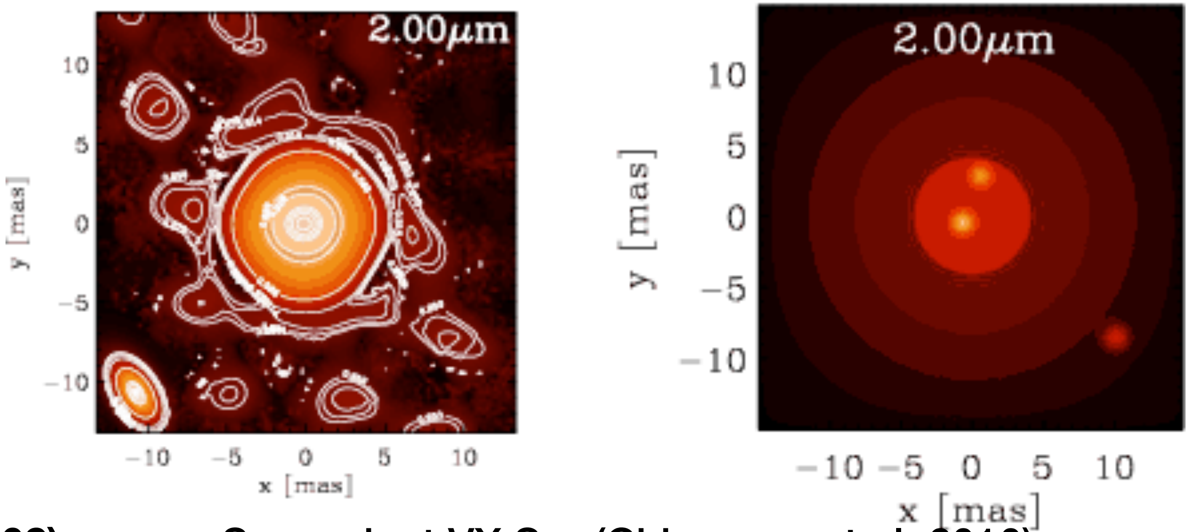
- Narrow (~1 km/sec)
- Velocity offsets up to a few km/sec
- Strong variability with phase
  - Mostly maser emission
  - Close atmospheric region
- Structure and dynamics of the atmosphere (positional accuracy to ~3 mas with current ALMA conf.)
- Onset of mass-loss and dust form.
- Modeling jointly with AMBER data

Wittkowski et al., in prep.

Imaging in the near-IR



Mira T Lep (Le Bouquin et al. 2009)



Supergiant VX Sgr (Chiavassa et al. 2010)

Limitations:

- *uv* - plane
  - Number of telescopes that can be combined simultaneously
  - Amount of data with different configurations
  - Ratio of largest baseline to shortest baseline
- Operational restrictions (available time, number of AT movements, good conditions needed)
- Imaging software